R-PARITY VIOLATION AND FLAVOUR VIOLATION

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The MSSM with R-Parity violation allows flavour changing neutral currents through two mechanisms, directly through one loop diagrams, and indirectly through the generation of flavour violation in the sparticle sector. We discuss the use of these mechanisms for constraining R-Parity violation, and show that the indirect mechanism parametrised in terms of the running of the soft masses from the unification or Planck scale typically dominates previously calculated effects. We discuss neutrino mass generation, $\mu \to e\gamma$, $b \to s\gamma$, and $K^0 - \bar{K}^0$ mixing as examples.

1 Introduction

One of the most promising candidates for physics beyond the so-called Standard Model (SM) is that of supersymmetry (SUSY). In this paper we shall be concerned with the implications of a particular possible feature of SUSY, namely that of R-parity violation (RPV).[1,2,3] R-parity is a $\mathbb{Z}_2$ symmetry of both the SM and its minimal SUSY extension, the MSSM, under which all of the SM particles have charge 0, while all their SUSY partners have charge 1. Its implications include the stability of the lightest supersymmetric particle (LSP), and hence the typical SUSY collider signatures of missing E_T and the existence of a source of dark matter. Its violation changes both the implied cosmology and the expected collider signatures, allowing such effects as LSPs decaying inside the detector and leptoquarks. In addition to these, further constraints on RPV can be derived by considering experimental limits on rare decays.[4,5,6]

R-parity is violated by the superpotential and soft potential terms

$$\begin{aligned}
W^{RPV} &= \frac{1}{2}\lambda_{ijk}L_iL_je_k + \lambda'_{ijk}L_iQ_jd_k \\
&\quad + \frac{1}{2}\lambda''_{ijk}u_id_jd_k + \mu_iL_iH_2 \\
V^{RPV}_{\rm soft} &= \frac{1}{2}C_{ijk}L_iL_je_k + C'_{ijk}L_iQ_jd_k \\
&\quad + \frac{1}{2}C''_{ijk}u_id_jd_k + D_iL_iH_2 \\
&\quad + m^2_{L_ih_1}L_iH_1^* + h.c. \qquad (1)
\end{aligned}$$

From the point of view of deriving constraints on the R-parity violating couplings in the model, the most extensively studied couplings are the dimensionless couplings λ, λ', and λ'', which directly generate many effects which can be experimentally limited. The extra soft terms by definition mostly couple only heavy SUSY particles and hence are relevant mostly because of their impact on the RGEs, although they can have significant effects on the neutrino-neutralino and Higgs-sneutrino sectors.[3,7,8,9]

In SUSY models, flavour changing effects may be caused by the existence of off-diagonal terms in the sfermion mass matrices in the basis in which the fermion masses are diagonal. Such flavour-violating soft masses can be generated either from the high energy theory such as a GUT directly, or else through the RGEs by couplings which violate flavour symmetries, such as Yukawa couplings mediated by the CKM matrix or here RPV couplings.

This paper is a short summary of work contained in two previous papers,[9,10] in which we presented the renormalisation group equations (RGEs) for the couplings of the full R-parity violating sector of the model, and investigated the implications of typical scenarios at the GUT scale for the generation of neutrino masses and other flavour violation processes.

2 Effects of the RGEs

We begin with a brief discussion of the dimensionless couplings, whose RGEs have recently been presented in a number of papers.[9,11] Here we present simple analytic solutions to the RGEs in the limit where the Yukawa couplings are much

smaller than the gauge couplings [9] leading to

$$\begin{aligned} \lambda(M_Z) &= 1.5\ \lambda(M_{GUT}) \\ \lambda'(M_Z) &= 3.4 - 3.7\ \lambda'(M_{GUT}) \\ \lambda''(M_Z) &= 4.0 - 4.7\ \lambda''(M_{GUT}) \end{aligned} \tag{2}$$

where the ranges are caused by the error on $\alpha_3(M_Z)$. In addition to running themselves, the RPV couplings can alter the mass spectrum, giving quite a tight constraint on the λ' couplings from the requirement that the sneutrino mass should be above its experimental limit,[10] and can generate patterns of soft masses which violate flavour and lepton number symmetries.

3 Sneutrino VEVs

Sneutrino VEVs are an important signature of R-parity violation which arise because of the existence of μ_i, D_i, and $m^2_{L_iH_1}$ terms which explicitly cause the effective potential to contain terms linear in the sneutrino field, either from explicit [3,8,12] or spontaneous R-parity violation. They can also be caused by one loop effects involving dimensionless R-parity violating couplings,[13,14] and by generation from the RGEs [9] as discussed below. Once sneutrinos have acquired VEVs, neutrinos and neutralinos mix, so that we may derive bounds on R-parity violating terms by imposing experimental limits on neutrino masses, since in general we find that with l_i as the VEV of L_i, a neutrino mass is generated is of order $(g_1^2+g_2^2)l_i^2/2M$, where M is some typical neutralino mass.

If we assume universal soft masses, then at the GUT scale we have only R-parity violation dimensionless and trilinear terms. The dangerous terms for generating sneutrino VEVs are then generated by the following terms mixing L_i and H_1.

$$\begin{array}{lcll} \lambda_{i33}h_\tau & \text{or} & \lambda'_{i33}h_b & \text{generating } \mu_i,\ D_i,\ m^2_{H_1L_i} \\ C_{i33}h_\tau & \text{or} & C'_{i33}h_b & \text{generating } D_i \\ C_{i33}\eta_\tau & \text{or} & C'_{i33}\eta_b & \text{generating } m^2_{H_1L_i} \end{array} \tag{3}$$

The effects are largest when $\tan\beta$ is large, but the dependence is rather complicated. The sneutrino VEV will in general be proportional to the R-parity violating coupling, and hence the neutrino mass to the coupling squared.

We have performed a GUT scale analysis, setting universal parameters at the unification scale, together with some choice of GUT scale R-parity violating Yukawas, then running masses and couplings to low energy to give output. Unfortunately, the behaviour is a sufficiently complicated function of the many different parameters that it is not really possible to derive useful bounds on the couplings, but it is nonetheless possible to get an idea of the order of magnitude of the neutrino mass which we expect. For example we find that λ_{133} and λ'_{133} of order 10^{-3} and 10^{-4} are still large enough to be inconsistent with present experimental limits over much of parameter space.[9]

4 Rare and Forbidden Processes

4.1 $\mu \to e\gamma$

One of the most tightly bounded experimental constraints on flavour changing neutral currents is through the rare decay $\mu \to e\gamma$, forbidden in the SM. In SUSY models, a non-zero rate can be generated through non-diagonal slepton mass matrices and also through the direct effects of R-parity violating couplings.[3,12,13] However, as noted above, R-parity violation induces flavour violation through soft terms, and so here we shall consider the two effects together. We shall set only two R-parity violating dimensionless couplings non-zero at M_{GUT} and see what effects they generate. We will be mainly interested in comparing the relatively simple "direct" contributions from diagrams which have R-parity violating couplings at the vertices, with the "indirect" contributions where the flavour violation is driven by off-diagonal mass insertions Δm^2 generated through the RGEs.

As an example we consider the impact of $\lambda'_{111}(M_{GUT}) = \lambda'_{211}(M_{GUT}) = 0.001$. We show the resulting contributions to the amplitude as a function of $M_{1/2}$ in Figure 1. Here we have set $\tan\beta = 10$, $m_0 = 100$GeV, $A_0 = 0$, $\mu_4 > 0$. What is remarkable about this figure is that it is clear that in this case the direct contributions are completely negligible relative to those from the chargino and neutralino mediated diagrams.

We conclude this section by summarising our results. Firstly we find rather different behaviour for the three different scenarios of non-zero λ', $LH\ \lambda$ (where the flavour violation occurs in the left handed slepton sector through $\lambda_{1ij}\lambda_{2ij}$) and $RH\ \lambda$ (where it occurs in the right handed slepton sector through $\lambda_{ij1}\lambda_{ij2}$). For the λ' case, the chargino and neutralino mediated diagrams

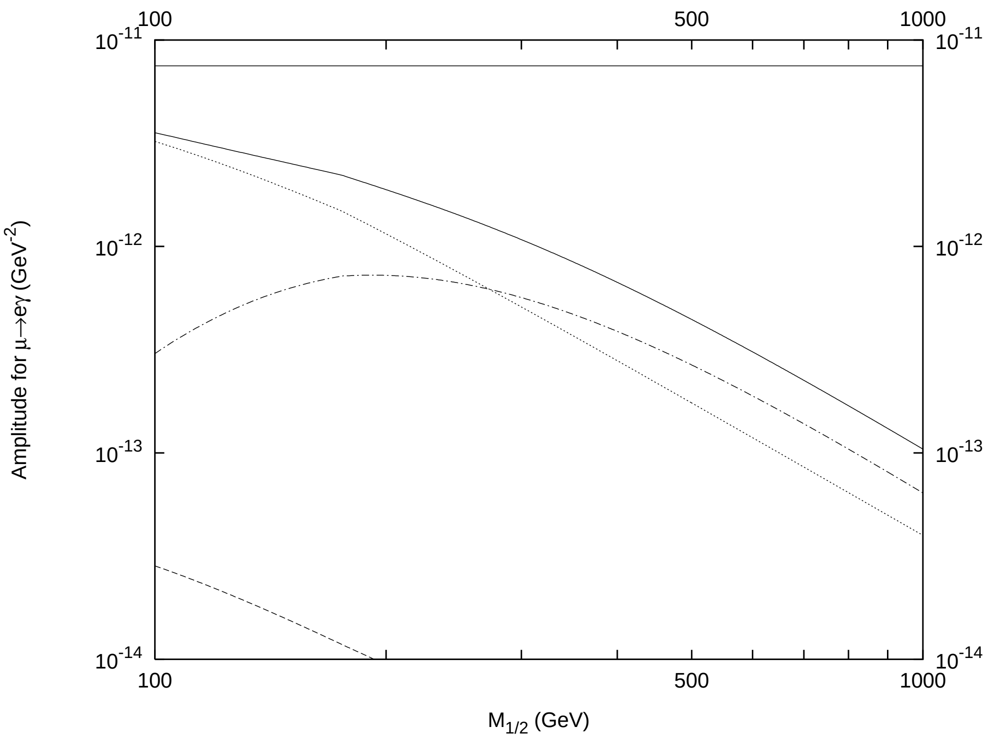

Figure 1: Absolute values of amplitudes for $\mu \to e\gamma$ from direct R-parity violation diagrams (dashed lines), neutralino mediated diagrams (dot-dashed lines), and chargino mediated diagrams (dotted lines) plotted against $M_{1/2}$. We also show the total amplitude (solid line) and the experimental bound on the amplitude (horizontal solid line). Parameters are $m_t = 175\text{GeV}$, $\alpha_3(M_Z) = 0.12$, $\tan\beta = 10$, $m_0 = 100\text{GeV}$, $A_0 = 0$, $\mu_4 > 0$, and $\lambda'_{111}(M_{GUT}) = \lambda'_{211}(M_{GUT}) = 0.001$.

with flavour violation through soft mass insertions dominate completely the direct contributions, giving very much tighter constraints, particularly for large $\tan\beta$. For the LH effects due to λ couplings we find again that the chargino contribution dominates, but not overwhelmingly, and there can be large cancellations. For the RH case there are no chargino contributions, and the neutralino and direct effects are usually of comparable size and opposite sign. However, since there are so many possible cancellations between terms, it is essentially impossible to derive concrete bounds. The strongest reasonable statement is that, for the values we have considered for pairs of couplings at M_{GUT} of $\lambda\lambda \simeq 10^{-4}$ and $\lambda'\lambda' \simeq 10^{-6}$ we expect contributions of order the experimental limit for a very light spectrum, with the branching ratio scaling as λ^4 or λ'^4 respectively.

4.2 $b \to s\gamma$

Another process which has been studied in the context of constraining flavour violation in SUSY theories is that of $b \to s\gamma$. Here we find that the indirect effects again often dominate the direct ones. However, the bounds on couplings derived here are quite weak, since $b \to s\gamma$ is much harder to constrain as the large SM contribution complicates matters, and indeed we find that the bounds on λ' are weaker than those derived from requiring the sneutrino mass to be above its experimental limit, while those on λ'' are only of order 0.2 for the relevant product with a very light spectrum.[10]

4.3 $K^0 - \bar{K}^0$ Mixing

The final process which we shall consider is that of $K^0 - \bar{K}^0$ mixing, the direct contributions to which have been extensively studied.[2,15] Here we find a complete contrast to the situation for the other processes, in that even when the large tree

level contribution is neglected the indirect contributions are always smaller than the direct ones.[10]

5 Conclusion

The full RGEs for the MSSM with R-parity violation with the inclusion of all soft terms as well as all dimensionless couplings lead to some interesting physics. The most important effects of including R-parity violating couplings at the unification scale are those associated with flavour violation, both through "direct" terms where these couplings appear at the vertices of the diagrams, and "indirect" terms where they generate off-diagonal soft masses through the RGEs which then generate effects through one loop diagrams.

The inclusion of R-parity violation in our superpotential through dimensionless terms allows the generation of lepton-Higgs mixing which leads to sneutrino VEVs and hence neutrino masses. We have shown that the indirect generation of sneutrino VEVs through the running of the RGEs for the soft terms often leads to larger effects than those derived directly from one loop diagrams. Typically we find that values of λ_{i33} and λ'_{i33} of order 10^{-2} and 10^{-3} respectively at the GUT scale give masses to the corresponding neutrino of order hundreds to thousands of eV, although the exact value is quite dependent on the unification scale parameters, and these form the tightest constraints on these couplings which have been derived.

Similarly, we have studied the process $\mu \to e\gamma$, which we have shown to be very strongly affected by chargino and neutralino mediated diagrams. These typically dominate the direct contributions which had already been calculated, often by several orders of magnitude for the case of the λ' couplings, but there are strong cancellations so that it is not possible to give precise bounds on the couplings from such processes. However, unless we invoke arbitrary cancellations, the typical size of such indirect effects on FCNC are likely to be the dominant constraint on the building of a model with non-zero R-parity violating couplings. In comparison, bounds derived from $b \to s\gamma$ are extremely weak except where the spectrum is already experimentally ruled out, while for $K^0 - \bar{K}^0$ mixing the direct contributions dominate.

Our main conclusion from these calculations is that R-parity violation can generate large flavour violating effects through the running of the dimensionful RGEs, and that these effects are often much larger than those which are generated directly by the couplings themselves, so that merely studying diagrams with R-Parity violating vertices can be very misleading.

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